An Earth-to-Deep-Space Optical Communications System With Adaptive Tilt and Scintillation Correction Using Near-Earth Relay Mirrors

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Abstract. The performance of an Earth-to-space optical telecommunications system is degraded by distortion of the beam as it propagates through the turbulent atmosphere. Conventional approaches to correct distortions, based on natural or artificial guide stars, have practical difficulties or are not applicable for correcting distortions important for Earth-to-deep-space optical links. A new beam-relay approach which overcomes these difficulties is presented. A downward-directed laser near an orbiting relay mirror provides a reference for atmospheric correction. The ground station pre-distorts its uplink communications beam such that, after passage through the atmosphere, uplink propagation effects are removed. The orbiting mirror then directs the corrected beam to the distant spacecraft. Discussion of this system is given.

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I. Introduction

It is now clear that optical telecommunications will be the next technological step in Earth-to-space communication. However propagation of an optical beam through the irregular atmosphere results in significant distortion of the signal, necessitating correction schemes for deep-space communications. Adaptive optics to correct for some atmospheric propagation effects have been used successfully in many astronomical[1] and 'Star Wars'[2] applications. These correction schemes require the presence of a 'glint'--an optical reference source--very near the target direction. In astronomical applications, for example, a laser-produced artificial guide-star (AGS) in the upper atmosphere, nearby the target direction, has been successfully implemented to correct high-order optical distortions[3].

For optical telecommunications, adaptive optics will be important for high-data rate downlinks and coherent communications applications. For the uplink, the low-order optical distortions--in particular the 'tilt' or transverse gradient of the optical phase--are of particular importance. The tilt of the wave is the instantaneous direction of the beam; if the tilt is too large, the beam is not pointed at the target and the link is degraded or lost completely. The situation is particularly acute for the uplink in very long distance communication (e.g., Earth to Pluto) where approximately diffraction-limited beams are required to deliver adequate signal strength to the distant spacecraft.

The atmospheric tilt can be quantified[4,5] through the integrated phase structure function, $D_\phi(r)$ = the mean-square difference of the geometric-optics phase at a transverse separation r in the receiving plane. If the three-dimensional spectrum of refractive index fluctuations, $P_{3n}(\mathbf{q})$ is an isotropic powerlaw over a range of wavenumbers between the reciprocals of any inner and outer scales ($P_{3n}(\mathbf{q}) = C_n^2\, q^{-\beta}$, where q is the modulus of the wavenumber), if $\beta < 4$, and if r is much larger than any inner scale and much smaller than any outer scale, then $D_\phi(r) \sim (r/b_{coh})^{\beta-2}$. Here b_{coh}, the coherence scale, is the scale over which the rms phase difference is 1 radian. For isotropic Kolmogorov turbulence $\beta = 11/3$ and $D_\phi(r) = (r/b_{coh})^{5/3} = 6.88\ (r/r_o)^{5/3}$, where r_o is the Fried parameter. A typical refractive tilt is $(\lambda/2\pi)$ grad(ϕ) $\sim\lambda/(2\pi\ b_{coh})$. At 1 micron, r_o can be ~10 cm at astronomical sites such as the Table Mountain Facility in California. Thus a D = 1 meter telescope typically has $D \gg r_o$ and, without compensation, has tilt-errors that can be large compared with the diffraction limit.

In this paper we outline difficulties with conventional schemes for atmospheric correction as they are applied to long-distance (Earth-to-deep-space) optical telecommunications systems. We then describe a new approach which can overcome the problems for propagation through the irregular atmosphere. This new system will be able to provide precise adaptive tilt and scintillation correction for a deep-space communications link.

II. Difficulties with Artificial Guide Stars in Optical Telecommunications Applications

Given existing laser technology, the large distance between the Earth and a distant spacecraft at Pluto (~30 AU) will require the optical uplink between the Earth and space probe to be near diffraction-limited from a 1 meter aperture. Turbulence-induced tilt of the wave, usually greater than the diffraction limit, becomes crucial; without tilt correction the signal from Earth is degraded or could miss the targeted spacecraft completely.

Several methods have been suggested to correct for optical propagation through the atmosphere, particularly in an astronomical imaging context. These all involve natural guide stars or producing one or more AGS reference sources at or near the desired uplink direction. These schemes are still under development, and their final performance depends on the applications they are used for. AGS-based correction methods, when applied to the uplink optical telecommunications problem as distinguished from the imaging problem, present unique difficulties. We outline these difficulties below so as to contrast these approaches with the beam relay solution we propose here.

(1) The obvious way to measure and correct the tropospherically-induced tilt and higher perturbations is to use a natural star[6] nearby the desired uplink direction as the reference source. However the star must be both bright (to get enough photons to sense the tilt in the ~1-100 milliseconds before it changes significantly[7]) and near the desired direction (to assure that the turbulence-induced distortion is highly-correlated between the reference star and the uplink beam direction). This latter requirement can be stringent when high correlation of the two optical paths is necessary. Bright stars nearby a desired target direction are not, in general, available, so this natural-guide-star scheme is not practical for operational, high-availability communications systems.

(2) An alternative to natural guide stars for astronomical imaging is to form a monochromatic AGS, produced from a transmitter site co-located with the telescope. Such a system cannot be used to measure and correct the tilt of the wavefront, however. This is because the atmospheric tilt is common to both the laser beam propagating up through the atmosphere and the back-scattered light from the AGS. The result is that the tilt cannot be sensed--thus cannot be corrected--by this scheme.

(3) More elaborate artificial polychromatic guide star systems, which exploit the dispersion in the refractive index of air between the ultraviolet and the infrared, have been proposed for tilt measurement. The idea is to break the symmetry of the upward-going and

downward-going paths by exciting mesospheric sodium with laser beams at 589 nm and 569 nm. When the atoms relax, they fluoresce at wavelengths between 0.33 and 2.3 microns. The dispersion of the refractive index causes the tilt to be different at different wavelengths; observation of the angular offset of the AGSs at different wavelengths allows the tilt to be solved for[8]. This approach is still under development and a potential difficulty with a practical implementation is generating sufficient laser power to allow for diurnal and seasonal variations in the sodium column density.

(4) Two or more monochromatic AGSs produced by laser transmitters physically separated from the main telescope have been proposed. In suitable circumstances the tilt in the target direction can in principle be deduced. The technical difficulties with a practical implementation of this idea have been discussed in the literature.[9]

(5) An optical downlink from the spacecraft itself cannot be used as an "AGS" reference source for two reasons. First, the optical downlink from a distant spacecraft will be very weak and will not give adequate SNR to estimate and correct the distortions of the beam. Second, and more fundamentally for an optical communications system operating in the visible, the downlink photons will in general be arriving from the wrong direction. Because of aberration introduced by the relative velocity of the ground and spacecraft the downlink and uplink directions are separated; the difference between the apparent direction of the downlink and the required pointing direction of the uplink will be $2\ \Delta v/c$, where Δv is the relative transverse velocity of the ground station and spacecraft. Typically Δv for a deep space probe will be dominated by the Earth's orbital speed $\approx$30 km/sec, so that the typical aberration angle will be $\approx$200 microradians. This is far larger than the isoplanatic angle for observations in the visible (but comparable to the isoplanatic angle in the near infrared[10]).

A new way to communicate from the ground to a distant spacecraft in the presence of atmospheric distortions of the optical beam and which obviates the difficulties with conventional guide stars is needed.

III. The Beam Relay System

Since optical propagation in interplanetary space is distortionless and since there is negligible uncertainty in the location of the spacecraft relative to a near-Earth point outside the Earth's atmosphere, a correctly-pointed diffraction-limited optical beam can be sent from a point outside the Earth's atmosphere to the spacecraft without scintillation or tilt error. This diffraction-limited beam could be formed by a transmitter above the atmosphere *or by a mirror* which re-directs a beam coming through the atmosphere from the ground. Since we are concerned here with a ground-based system, the relay mirror scheme will be considered.

The essence of the idea is that a relay mirror is located in Earth orbit, above the distorting atmosphere. A reference beam providing the information necessary for the ground-based adaptive optics to correct for the atmosphere and thus deliver a diffraction-limited beam to the orbiting relay mirror is produced from a small laser source (~1 mW through ~10-cm optics). The reference source is slightly physically offset from the relay mirror to allow for aberration caused by relative velocity of the ground and the relay mirror. The relay mirror directs the uplink communications beam towards the distant spacecraft with the required pointing accuracy. A sketch of this relay system is shown in Figure 1. An essential feature of this system is that it has a bright reference source, generated above the atmosphere, and at the same angular position where the uplink beam must go through the atmosphere. Under this condition, adaptive optics can be used to correct the uplink beam for the propagation-induced distortions generated by its passage through the atmosphere. Unlike other atmospheric compensation approaches, the beam relay approach offers the ability to monitor in space the degree of compensations achieved on the uplink. By placing optical detectors in the interstices between mirror segments, one can monitor and map the optical power distribution across the aperture. These data are relayed to the ground station along with metrology data on the mirror segments. With appropriate registration of the detectors, they provide real time information on the irradiance pattern at the relay mirror and of the beam directed to the spacecraft.

IV. Design Considerations of the Relay System

The beam relay system proposed here fundamentally solves the principal problem: the laser reference source for the adaptive optics is above the atmosphere, the tilt is estimated from a wave that makes only one passage through the troposphere, and the reference beam can be used to produce a diffraction-limited communications beam which can be aimed accurately at the relay mirror.

Specific system design considerations and advantages are discussed below.

(1) Reference Beam Power

The orbiting laser that provides the reference should be bright enough for very rapid (~millisecond) tilt- and higher-order corrections. This can be accomplished with a modest-power laser using small optics. The signal-to-noise ratio (SNR) for the adaptive optics system will be limited by some combination of sky background (which can be made small with appropriate filters) and receiver noise. The shot-noise limited receiver SNR is η P_R/(2

$h \nu B$), where η is the quantum efficiency, P_R is the received power, h is Planck's constant, ν is the photon frequency, and B is the receiver bandwidth. As an order-of-magnitude calculation: if the light from a 1mW laser at $\lambda \sim 1$ micron on a spacecraft at geosynchronous orbit were transmitted to the Earth through ~10 cm optics, then the diffraction-limited spot size on the Earth would be ≈350m. A 1 meter telescope on the ground would thus collect $P_R \approx 8$ nW of the transmitted power. Taking $\nu \approx 3 \times 10^{-14}$ Hz and $B \approx 1000$ Hz gives shot-noise SNR ≈ 69 dB. (Daytime operations will be possible with SNR reduced owing to sky background noise. Even for observations at 1 micron--with 100 microradian field-of-view, filter bandwidth $\Delta\lambda \approx 1$ angstrom, and looking $\approx 10^{\circ}$ from the sun--sky background contributes only a few percent of the power received from the spacecraft reference beam.) Thus moderate-power reference beams provide SNR adequate for rapid, high-quality estimation and correction of atmospheric tilt and scintillation.

(2) Relay Mirror

The reflector need not be a single large mirror (there probably good reasons to synthesize the aperture from smaller, cheaper, easier-to-control segments.) The relay mirror (or mirror segments) could be flat--no special figuring of the mirror(s) is necessarily required. System engineering trade-offs (e.g., size of reflector/number of segments versus distance to the orbiting mirror; complexity of tracking a low-Earth orbiter versus simplicity of the spacecraft) can be made. For example, suppose that the relay mirror structure were in geosynchronous orbit. The diffraction-limited beam for a D = 1 meter telescope operating at $\lambda \sim 1$ micron would be $\lambda/D \sim 10^{-6}$ radians. After propagating a distance $z \approx 3.6 \times 10^{7}$ m to geosynchronous orbit, the spot would be limited by diffraction to a size $\sim z \lambda/D \sim 36$ meters. For a relay mirror in geosynchronous orbit, the beam would thus be ≈36 meters across; the relay's aperture would have to be ~36 meters across to capture the uplink power and relay it to the deep space probe. Moving the orbiting relay station to low Earth orbit or possibly on an airship at very high altitude (smaller propagation distance, z) obviously reduces the required relay mirror aperture to ~few meters (depending on the ground-station-to-relay range during the tracking pass). This reduction in relay aperture can be traded off against the complexity of tracking the relay mirror that in this case moves across the sky as seen by the ground station.

(3) Uplink Pointing

Consider the case where the relay mirror is in geosynchronous orbit. The relative velocity of the Earth and mirror is well-known and extremely slowly varying with time. The reference source would be on a separate small spacecraft ≈600 meters away from the relay mirror, placed such that the reference source is in the correct position to correct for aberration ($2\ \Delta v/c \approx 17$ microradians; here Δv is dominated by the orbital speed of the relay around the earth). The uplink is then pointed at the apparent position of the reference beam, in order to hit the orbiting relay mirror.

The refractive tilts observed on the downlink will in general be larger than the diffraction-limited divergence and also time-variable. Despite this, the pointing of the uplink communications beam is only back toward the apparent position of the reference beam. (We desire to relay the beam to the distant spacecraft with a pointing accuracy at least equal to the diffraction limit, $\sim 10^{-6}$ rad for the example above. Thus the angle of incidence of the wave onto the relay mirror must be accurate to this tolerance in the presence of refractive tilts ~10-or-more times larger than this. The tilts are, however, produced in the atmosphere close to the Earth, while the relay mirror is very far away. Thus, if the communications beam is directed straight back toward the apparent position of the reference beam, the angle-of-arrival variations at the relay mirror will be reduced compared with the atmospheric tilt angle variations by a geometrical leveraging factor ≈(distance of ground station to a typical scattering element in the troposphere)/(distance of ground station to the relay mirror). This factor is of order 0.01-0.001 for a relay mirror at geosynchronous orbit, so that the beam will be accurately relayed to the distant spacecraft even if the uplink communications beam simply points back at the reference source.)

(4) Atmospheric Heating by the Uplink Beam

The uplink communications beam must have relatively high power for communications throughout the solar system. Some fraction of this power will be absorbed by the atmosphere, resulting in temperature gradients that will contribute to refractive steering of the beam. The extent of this heating depends on the opacity of the atmosphere at the wavelength of the uplink radiation and the beam power. Any tilt variations produced by beam heating will, however, be largely common with the downlink reference beam, thus sensed and corrected by the adaptive optics system.

(5) Focus Anisoplanatism

There is no focus anisoplanatism in this realization. Laser AGSs are produced at altitudes less than or about 95 km. The backscattered AGS light thus senses atmospheric perturbations in a roughly conical volume, with the cone's apex at the AGS position and the base at the ground station mirror. The actual optical path to the distant spacecraft (a cylinder through the atmosphere) is different, however. The reference source generated in our proposed method with the laser in geosynchronous orbit is sufficiently far away that it effectively samples the same atmosphere that the communications beam propagates through.

(6) Relay Mirror Pointing

As envisioned here, the relay mirror is a space-borne structure with characteristic dimension, depending on the orbit chosen, of up to a few tens of meters. To relay the uplink communications beam accurately to a distant spacecraft, the relay mirror must be oriented in space to better than 10^{-6} radians (the structure itself need not be oriented to that accuracy, only the control points defining mirror or mirror segment positions). The spacecraft target position would be determined within a reference frame of relatively bright stars. After acquiring these guide stars, the structure would then be oriented to the correct position for beam relay. For 10^{-6} radian orientation errors, control points at the ends of the relay structure would need relative positions controlled to ~40 microns. Technology experiments on space shuttle missions have already demonstrated 30 meter structures (passively deployed) and 14 meter (assembled) structures with 1mm accuracy. In support of near-future optical interferometry/astrometry in space, there is current research for assembly of lightweight ~100 meter structures with elements located to ~100 microns which are contemplated for some flight configurations. The beam relay system will benefit from this and other technology development (vibration isolation, laser metrology to measure positions of optics) for large structures in space[11].

(7) Astronomical Applications

The system described here is for uplink telecommunications. By repositioning the spacecraft providing the reference source closer to the relay the system could, in principle, also work as a diffraction-limited receiver of light reflected from the relay mirror. However astronomical uses will be severely limited by the very small field of view of the aggregate system. The relay mirror subtends an angle only equal to the diffraction limit of the ground station. Thus only a small part of the sky, of angular dimension ~10^{-6} rad for the example parameters given above, would be instantaneously "visible" (and thus correctable to the diffraction limit) in the relay mirror. This limited field-of-view could effectively be enlarged by scanning the relay mirror, but at the expense of much longer integration times.

V. Summary and Conclusion

Uncompensated propagation through the Earth's turbulent atmosphere fundamentally degrades optical communications with distant spacecraft. The communications consequences, particularly on the uplink, of these atmospheric distortions are more pronounced as the communication distance increases. Of particular concern is the tilt of the wavefront. Tilt cannot be corrected using natural stars (in practical, high-availability systems) or with currently demonstrated artificial guide star techniques. Using a relay mirror in geosynchronous orbit and a bright laser reference source offset slightly from the mirror to allow for aberration, it is possible to build an Earth-to-deep-space optical telecommunications link with precise adaptive tilt and scintillation correction. The bright reference source gives accurate correction information for the ground-based adaptive optical system to preprocess the uplink such that a diffraction-limited beam is delivered to the relay mirror, which in turn directs the uplink to the deep-space probe.

In conclusion, the beam relay system described here can serve the communications requirements of many missions. It guarantees accurate tilt and scintillation correction for a high-power Earth-to-deep-space optical communications link. Implementation of this system would use technology under development for other mission but does not require any major technological breakthroughs.

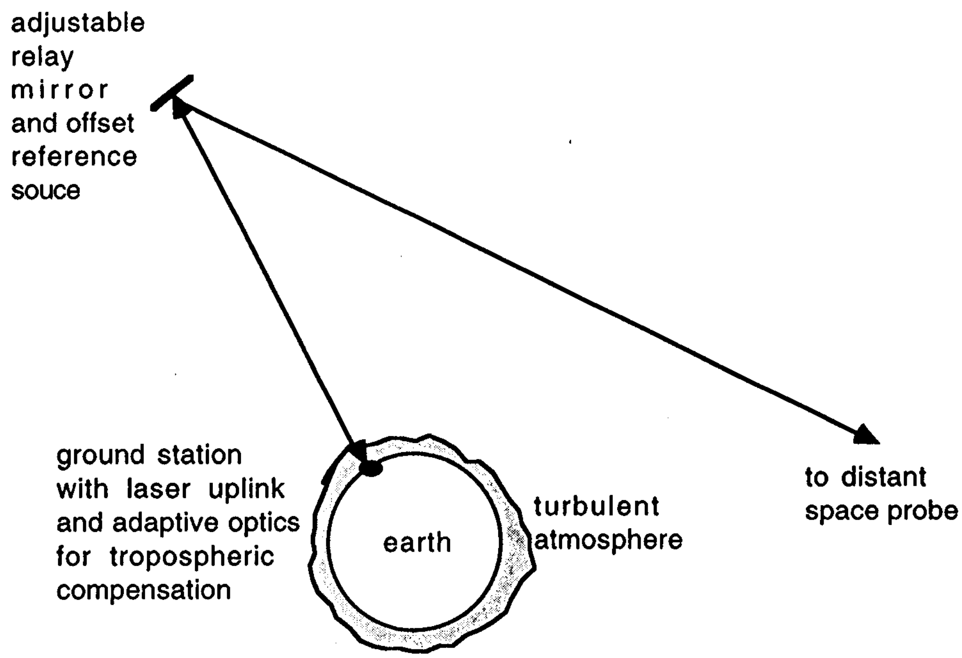

Figure 1. Schematic, not-to-scale, diagram of the optical telecommunications beam-relay system. The beam from a laser on a small spacecraft physically offset from the relay mirror (to compensate for aberration) propagates down to the ground, giving a reference for the adaptive optics on the ground station. The atmospherically-compensated uplink communications beam is transmitted to the relay mirror in orbit and then directed to the distant deep space probe.

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